Detectability of Upgoing Sleptons

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Abstract: Some supersymmetric models predicted long lived charged sleptons. Following Albuquerque, Burdman and Chacko[1], we consider an exact process where the $\widetilde{\tau}$, the supersymmetry partner of τ lepton, are produced inside the earth by collisions of high energy neutrinos with nucleons. We detailedly investigate the possible signals of upgoing $\widetilde{\tau}$ by comparing with the background muons where atmospheric neutrino flux is taken into account. The realistic spectra shows that km-scale experiments could see as many as 69 events a year by using the Waxman-Bahcall limit on the extraterrestrial neutrino flux.

Key Words: Slepton; Dark matter detection; Upgoing events

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1 Introduction

Substantial evidences exist suggesting that most of the Universe's matter is non luminous [2][3]. There are many predictions for its composition but the nature of dark matter is yet unknown.

Weak scale supersymmetric theories of physics beyond the standard model, provide perhaps the most promising candidates for dark matter[4]. However, supersymmetry must be broken at the energy scale accelerator having reached since the superpartners have not been observed yet. Supersymmetric models typically have a symmetry, called R-parity, which exclusively ensures that the Lightest Supersymmetric Particle (LSP) is the most stable. Obviously, the LSP is the natural candidate for dark matter. Different scales of supersymmetry breaking determine what the LSP is. Typically, if supersymmetry is broken at high scales, the LSP is likely to be the neutralino or the quintessino[5], however, if supersymmetry is broken at lower scales, the LSP is likely to be the gravitino[6]. In the models where the LSP is typically the quintessino or the gravitino, the Next to Lightest Supersymmetric Particle (NLSP) tends to be a charged slepton, typically the right-handed $\widetilde{\tau}$, which has a long lifetime between microsecond and a year around[5][6], depending on the scale of supersymmetry breaking and the slepton's mass. Of course, these lifetimes are negligible comparing with age of our

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universe, therefore, almost all these NLSP produced in the evolutive history of the universe decayed into LSP.

Lest to mislead the reader, we should clarify several points. It is not absolutely certain that the NLSP is either charged slepton or other neutral supersymmetric particle; furthermore, there is at present no direct evidence for the existence of supersymmetry. These are still unproven ideas. But some theoretical conclusions prefer the slepton to other neutral NLSPs [7]. Although speculative, supersymmetric dark matter is very well motivated and based on a simple physical principle.

In the models of Slepton as NLSP, since the slepton is massive, actually, it can possibly be produced by high energy process. Collisions of high energy neutrinos with nucleons in the earth at energies above threshold for supersymmetric production can produce supersymmetry pairs which are unstable and promptly decay into slepton; since the slepton is charged and long lived, it is worthy to see whether its upgoing tracks could be detected by some large cosmic ray experiments or neutrino telescopes, such as L3+C [8], ICECUBE [9], Super-K [10], etc. Based on a gravitino-LSP scenario, Albuquerque et al initiated that one can take neutrino telescopes as a direct probe of supersymmetry breaking[1]. Motivated by their work, our following calculations base on the quintessino-LSP scenario from Ref.[5] where it restricts the stau mass between $100GeV$ and $1TeV$ and the lifetime between $10^6 \sim 10^7$ seconds.

2   Fundamental Process Analysis

High energy neutrinos interacting with nucleons will produce supersymmetric particles, and that will promptly decay into a pair of NLSPs, which have long lifetime. This lifetime is definitely large enough so that $\widetilde{\tau}$ do not decay inside the earth. $\nu N \rightarrow \widetilde{l}\widetilde{q} \rightarrow 2\widetilde{\tau}$, the dominant process is analogous to the standard model charged current interactions, i.e, $\nu_\mu N \rightarrow \mu^- + anything$. We include the corresponding processes at the parton level in Figure 1.

We make use of the stau mass $m_{\widetilde{\tau}} = 143GeV$ and two values for the squark masses: $m_{\widetilde{q}} = 150, 300GeV$ [11] in our calculations, and the cross section for supersymmetric production as a function of the neutrino energy is given in Figure 2. Also plotted for comparison is the standard model charged current cross section [12]. From Figure 2 one can conclude supersymmetric interactions is much weaker than that of standard model.

3   Calculate upgoing fluxes

In order to be comparable with the results form Ref.[1], we consider the similar physical process. We take the earth as the target and consider the incoming of some diffuse fluxes of high energy neutrinos. In our calculations, we make use of a model of
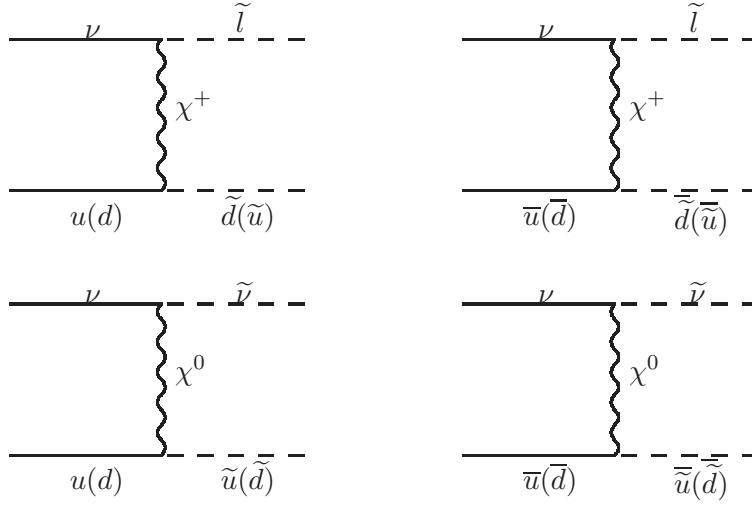
Figure 1: Feynman diagrams for supersymmetric particles production in νN collisions. the upper two diagrams refer to charged current interactions, and the under two diagrams account for neutral current process, with the exchanges of the chargino χ^+ and neutralino χ^0, respectively.
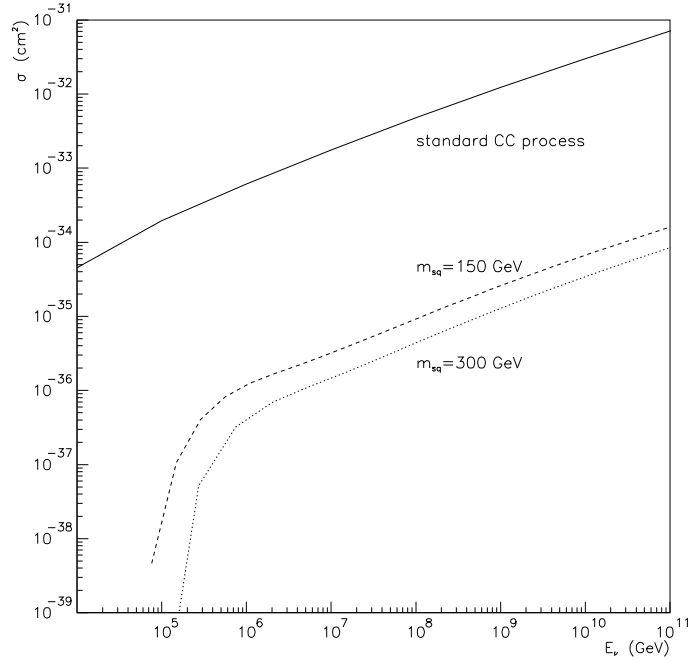

Figure 2: The cross section of νN interactions as a function of neutrino energy. The curves correspond to $m_{\widetilde{\tau}} = 143 GeV$ and for squark masses $m_{\widetilde{q}} = 150, 300 GeV$. The top curve refers to the standard model charged current interactions.

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the earth density profile as detailed in Ref.[12].

Dynamic analysis shows that the energy threshold for $\widetilde{\tau}$ production has to be over $\sim 100TeV$. For atmospheric neutrino flux, usually experimental data give its ranges from 1 to $10TeV$, which seems out of our need, however, theoretical results [13] show us that atmospheric neutrino spectrum with energy above $10TeV$ still act an important flux for $\widetilde{\tau}$ and muon production. We make use of atmospheric neutrino flux with energy under $10TeV$ in Ref.[14], and the flux with energy above $10TeV$ in Ref.[13].

Figure 3 summarizes some popular theoretical and experimental upper limits on diffuse neutrino fluxes. The Waxman-Bahcall (WB) upper bound [15] assumes that 100% of the energy of cosmic ray protons are lost to π^+ and π^- and that the π^+ all decay to muons that also produce neutrinos. Ref.[15] also discussed the maximum contribution due to possible extra-galactic component of lower-energy $< 10^{17}eV$, where protons have been first considered (max.extra-galactic p). Experimentally, AMANDA experiment gave a upper bound on diffuse neutrino flux [16]. By considering optically thick AGN models or by involving very strong magnetic fields, Mannheim, Protheore, and Rachen (MPR) have argued that one might be able to avoid the WB limit and get a higher upper bound [17]. From Figure 3, actually, for extraterrestrial neutrino flux, we can conclude that the upper bound has been decided by AMANDA experiment on the neutrino energy below 10^6GeV, therefore, we take "max.extra-galactic p" as supplement for the neutrino energy above 10^6GeV. In this article, unless extra specification, the following results all make use of atmospheric neutrion flux with energy above $1GeV$ adding the conservative extraterrestrial WB Limit as the incoming neutrino flux.

There are two factors must be taken into account: one is the attenuation of high energy neutrinos through the earth, the other is the energy loss of charged $\widetilde{\tau}$ before running into a detector.

The earth is opaque to ultra-high energy neutrinos. When the energy of neutrinos is over $40TeV$, the νN interaction length turns out to be larger than the diameter of the earth, the attenuation of neutrinos must be considered.

$$\mathcal{I}_\nu(E_\nu, x) = \mathcal{I}_\nu^0(E_\nu) \exp(-x/l), \qquad (1)$$

where $\mathcal{I}_\nu^0(E_\nu)$ is the initial incoming neutrino flux, x is the depth a neutrino penetrating the earth, and l refers to the interaction length, $l \equiv 1/(\sigma_{tot} \cdot n)$, n accounts for the number density of the medium. Here σ_{tot}, in principle, include all charged and neutral current processes contributing by both standard model and supersymmetric production. Since the initial interactions produce slepton and these are nearly degenerated in flavor, the flavor of the initial neutrino does not affect the results.

The upgoing $\widetilde{\tau}$ event rate depends on the νN cross section in two ways: through the interaction length which governs the attenuation of the neutrino flux due to interactions in the earth, and through the probability that the neutrino converts to a $\widetilde{\tau}$ energetic enough to arrive at the detector with $E_{\widetilde{\tau}}$ large than the threshold energy $E_{\widetilde{\tau}}^{min}$. The
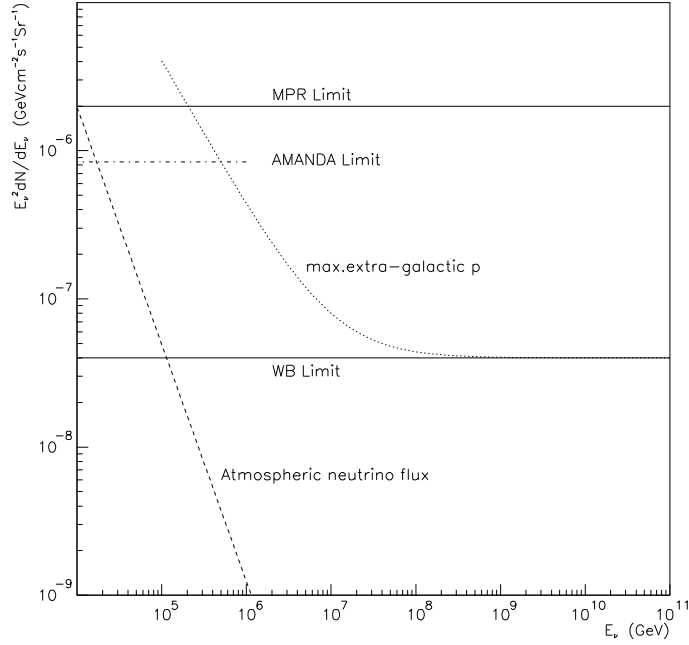
Figure 3: Neutrino fluxes given by different models. The WB bound line gives the upper bound corrected for neutrino energy loss duo to redshift and for the maximum known redshift evolution. The dot curve is the maximum contribution due to possible extra-galactic component of lower-energy. The dash-dot line shows the experimental upper bound on diffuse neutrino flux established by the AMANDA experiment. The top line is given by authors Mannheim, Protheore, and Rachen (MPR) with considering optically thick AGN models or very strong magnetic fields. Dashed line is the theoretic predict for energetic atmospheric neutrino flux.

probability that a $\widetilde{\tau}$ produced in a νN interaction arrives in a detector with an energy above the $\widetilde{\tau}$ energy shreshold $E_{\widetilde{\tau}}^{min}$ depends on the range R of a $\widetilde{\tau}$ in rock, which follows from the energy-loss relation [18]

$$-\mathrm{d}E_{\widetilde{\tau}}/\mathrm{d}x = \alpha + E_{\widetilde{\tau}}/\xi, \tag{2}$$

here, the coefficients α and ξ characterize the ionization and radiation losses respectively. For numerical estimates of ionization loss here we use $\alpha = 2MeV/(gcm^{-2})$ [19]. For a given momentum impulse, the radiation energy loss is inversely proportional to the square of the mass of the radiation particle. Thus the radiation length for $\widetilde{\tau}$ is approximately $(m_{\widetilde{\tau}}/m_{\mu})^2$ times large than that for muons. We take $\xi_{\mu} \approx 2.5 \times 10^5 g/cm^2$ in rock [18] and define $\epsilon \equiv \alpha\xi$, then the range can be expressed

$$R(E_{\widetilde{\tau}}, E_{\widetilde{\tau}}^{min}) = \xi \ln \frac{\epsilon + E_{\widetilde{\tau}}}{\epsilon + E_{\widetilde{\tau}}^{min}}. \tag{3}$$

The general solution of equation (2) is

$$E_{\widetilde{\tau}} = \left(E_{\widetilde{\tau}}' + \epsilon \right) \exp(-x/\xi) - \epsilon. \tag{4}$$

The left side of (4) is to be interpreted as the residual energy of a $\widetilde{\tau}$ of initial energy $E_{\widetilde{\tau}}'$ after penetrating a depth x of material.

For those $\widetilde{\tau}$ ranging into the detector and fixing energy at $E_{\widetilde{\tau}}$, they can be contributed by any initial $\widetilde{\tau}$ with the energy above $E_{\widetilde{\tau}}$ and being produced at the distance $R(E_{\widetilde{\tau}}', E_{\widetilde{\tau}})$, therefore, the differential flux intensity can be expressed:

$$\frac{\mathrm{d}N_{\widetilde{\tau}}}{\mathrm{d}E_{\widetilde{\tau}}} = 2\pi \int_0^{\frac{\pi}{2}} \sin\theta \mathrm{d}\theta \int_0^R N_A \rho(r) \mathrm{d}x \int_{E_\nu^{th}} \mathcal{I}_\nu(E_\nu, x') \frac{\mathrm{d}\sigma_{\widetilde{\tau}}}{\mathrm{d}E_\nu \mathrm{d}E_{\widetilde{\tau}}'} \mathrm{d}E_\nu, \tag{5}$$

Here, we define the zenith angle θ as the angle between the incident direction of neutrinos and the direction of the line linking the center of both the earth and the detector. N_A is Avogadro's number, $\rho(r)$ corresponds to the earth density, and $r = \sqrt{(x^2 + R_\oplus^2 + 2xR_\oplus \cos\theta)}$ is the distance from the center of the earth, where $R_\oplus$ refers to the radius of the earth. E_ν^{th} is neutrino threshold energy for $\widetilde{\tau}$ productions. $\frac{\mathrm{d}\sigma_{\widetilde{\tau}}}{\mathrm{d}E_\nu \mathrm{d}E_{\widetilde{\tau}}'}$ refers to the differential cross section of $\widetilde{\tau}$ productions. $\mathcal{I}_\nu(E_\nu, x')$ and $E_{\widetilde{\tau}}'$ are given by Equation (1) and (4), respectively. We take $x' = 2R_\oplus \cos\theta - x$ instead of the distance a neutrino travelling in the earth.

4   Possible signals analysis

High energy νN processes can produce $\widetilde{\tau}$ as well as muons. Obviously, the upgoing muons, as the background flux, will range into the detector accompanying with $\widetilde{\tau}$ by
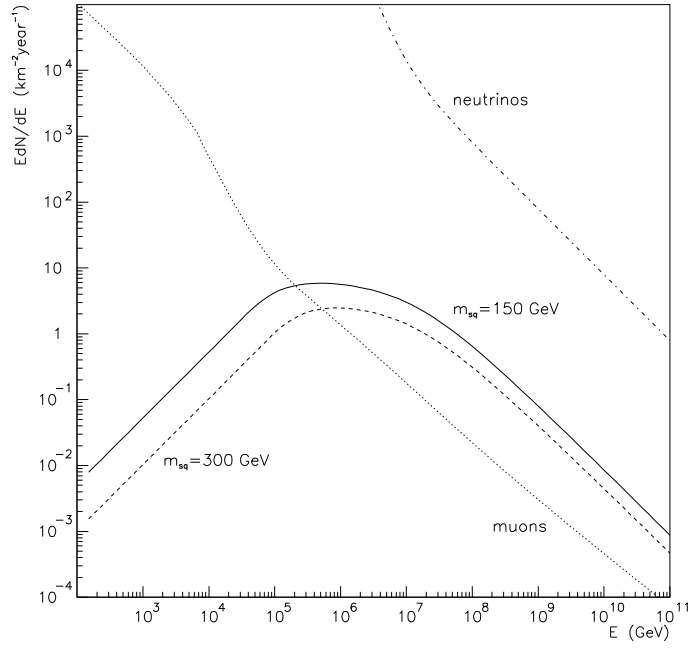
Figure 4: Energy spectrum of $\widetilde{\tau}$ pair events per km^2, per year, for $m_{\widetilde{q}} = 150, 300 GeV$. Also shown are the upgoing neutrino and muon flux through the detector. We make use of atmospheric neutrion flux with energy above $1 GeV$ adding the conservative extraterrestrial WB Limit as the incoming neutrino flux.
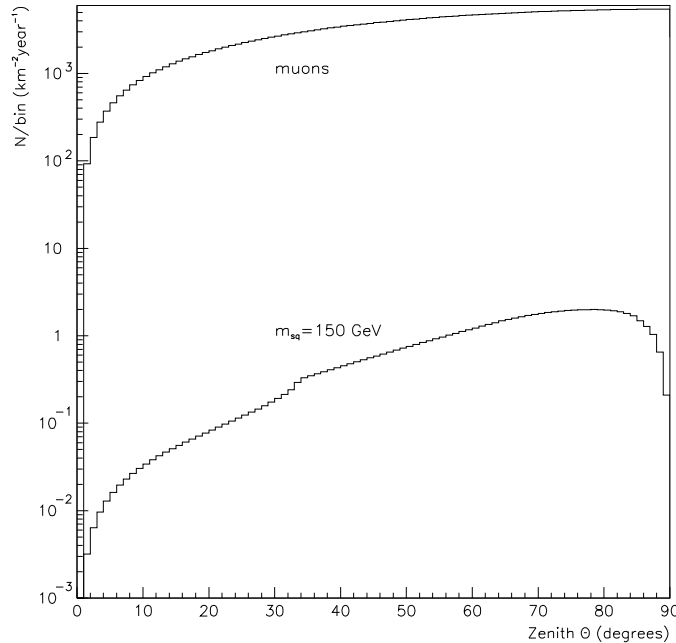
Figure 5: Angular distribution of $\widetilde{\tau}$ pair events per km^2, per year, for $m_{\widetilde{q}} = 150 GeV$.
Also shown are the muon flux. We make use of atmospheric neutrion flux with energy above $1 GeV$ adding the conservative extraterrestrial WB Limit as the incoming neutrino flux.

similar interacting process. There are several possible ways exist to distinguish the $\widetilde{\tau}$ signals from the background muons.

The first is its differential energy spectrum. Some detectors have very well energy resolution, typically, L3+C detector[8], can reconstruct the exact tracks of charged particles in the magnetic field, which can determine the momentum, charges and direction of the incident particles at last. This can possibly provides the direct evidences for some exotic particles. In Figure 4 we show the energy distribution for the $\widetilde{\tau}$ pair events for two choices of $\widetilde{q}$ masses: $150 GeV, 300 GeV$. Also shown is the upgoing neutrino flux as well as the energy distribution of upgoing muons'. We see that, the dominant contribution of $\widetilde{\tau}$ comes from the energy zones between $10^5 \sim 10^7 GeV$. This mainly because most of $\widetilde{\tau}$ are produced in the earth with the energy above $10^5 GeV$ and range into detector with high energy as well. However, with the energy of neutrinos growing, the range of $\widetilde{\tau}$ with the energy above about $10^8 GeV$ turns out to be lager than the diameter of the earth, therefore, all initial $\widetilde{\tau}$ can totally arrive at the detector, which makes the events rate curve almost parallel with that of incoming neutrinos. Comparing with the curve of $\widetilde{\tau}$ flux, we can see, the muon flux's is much stronger at the low energy zones($< 10^5 GeV$), and turn out to be weaker at the high energy zones($> 10^5 GeV$).

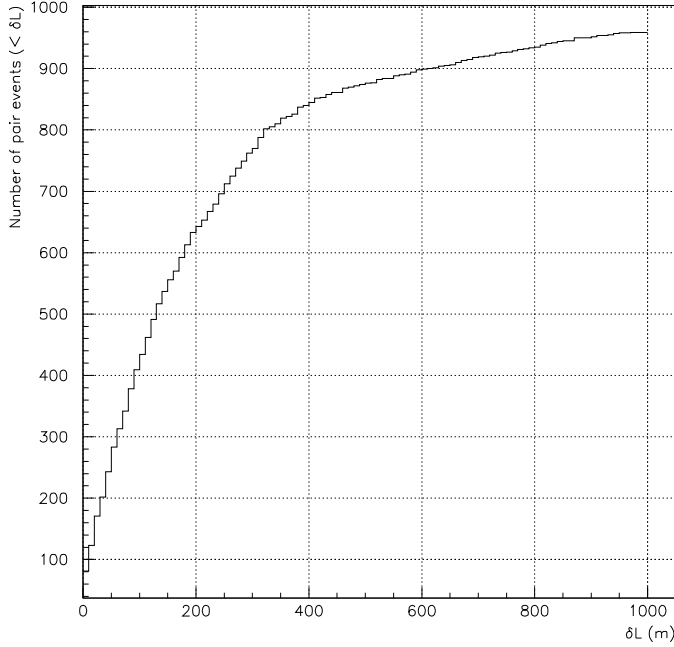The second is the angular distribution of events rate. Generally, neutrino telescopes

Figure 6: The Monte Carlo result for integral total 1000 pair events vs. their distance δL. We make use of atmospheric neutrion flux with energy above $1GeV$ adding the conservative extraterrestrial WB Limit as the incoming neutrino flux.

have poor energy resolution, only the angular resolution is used to reduce the background. Figure 5 shows us the angular distribution of events rate of $\widetilde{\tau}$ and muons. From the figure one can conclude that the angular distribution of upgoing $\widetilde{\tau}$ is definitely different from muon's. The dominant contribution of upgoning $\widetilde{\tau}$ comes from the solid angle between $70 \sim 80$ degrees. This is mainly because most of $\widetilde{\tau}$ have their energy between $10^5 \sim 10^7 GeV$ which hold the range about $10^9 cmwe$, this approximately equal to the acclivitous thickness of the earth at the directions between $70 \sim 80$ degrees. Therefore, to the isotropic incoming neutrinos within that directions, once interact with nucleons, the produced $\widetilde{\tau}$ will range into the detector totally. For most of muons, their ranges are neglectable comparing with the diameter of the earth, so the events will grow as the angle increasing. It is a pity that one can hardly reduce background through this method duo to the peak signals of angular distribution completely overlayed by muons'. Comparing with extraterrestrial neutrinos, atmospheric neutrino flux gives dominant contribution to the muon production.

The third is the tracks of the $\widetilde{\tau}$. The NLSPs are produced in pairs and that will promptly decay into $\widetilde{\tau}$ with the average energy $(E'_{\widetilde{\tau}})_{1,2} \approx 70\%(20\%)E_\nu$ [11]. As mentioned in Ref.[1], typical signal events include two tracks separated by certain distance

$$\delta L \approx D\vartheta, \tag{6}$$

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Table 1: Number of events per km^2 per year for taking WB, AMANDA+max.extra-galactic p and MPR as extraterrestrial fluxes, respectively. Atmospheric neutrino flux with the energy above $1GeV$ is taken into account as well. The first column refers to upgoing muons. The last two columns correspond to upgoing $\widetilde{\tau}$ for two different choices of squark masses: $150, 300GeV$.

	muon	$m_{\hat{q}} = 150GeV$	$m_{\hat{q}} = 300GeV$
Atmos.+ WB	4.83×10^5	69	26
Atmos.+ AMANDA+max.	4.90×10^5	470	139
Atmos.+ MPR	5.02×10^5	3164	1244

where D refers to the distance to the production point, and ϑ is the angle between the pair particles. Considering D to be the same order with $\widetilde{\tau}$ range, typically several hundred kilometers and ϑ within 10^{-3}, δL should typically be within several hundred meters. Figure 6 gives a Monte Carlo result for 1000 $\widetilde{\tau}$ pair events. We make use of atmospheric neutino flux adding extraterrestrial neutrino flux(WB) as input and consider an exact interacting process inside the earth, including different incoming directions, attenuation of neutrinos and $\widetilde{\tau}$, enery conversion from a neutrino to two $\widetilde{\tau}$, the range of a $\widetilde{\tau}$ running in the earth, etc. At last we get an integral distribution for number of pair events($< \delta L, 10m/bin$) vs. the distance δL, from which one can conclude that typical pair events hold the δL about $120m(\sim 50\%)$ and most of them are within the confines of $320m(\sim 80\%)$. Owing to all muon signals are single tracks, seeking double tracks signals turns out to be an effective method to distinguish from background. if we take the two tracks which both enter into a detector within $\delta t = 4$ microsecond as a double-track event, then for per km^2 per $year$, the accidental coincidence rate of muons is as few as $2N_\mu N_\mu \delta t \approx 6 \times 10^{-2}$, where N_μ refers to the number of events for muons.

In Table 1 we show the events rate for $\widetilde{\tau}$ pair production per km^2 per year on the atmospheric neutrino flux with the energy above $1GeV$ adding different extraterrestrial neutrino fluxes. For being comparable, we also show the rates of upgoing muons. Comparing with the results from Ref.[1], the number of events are increased at least an order of magnitude. This mainly because we work under the SUSY breaking scenario with a quintessino LSP instead of a gravitino LSP. According to the analysis given above, some large scaled detectors appear to be sensitive to the relatively long lived $\widetilde{\tau}$.

5 Conclusions

We discussed the exact production process of upgoing sleptons based on the long lifetime scenario with a quintessino LSP. Furthermore, we detailedly investigated the possible signals of events: energy spectrum, angular distribution and their tracks, from

which one can conclude that the characteristic signals of events are distinctively different from that of background muons'. The study shows that seeking double-track upgoing events is a feasible method to detect $\widetilde{\tau}$ signals. It's worth to mention that we introduced the contribution from atmospheric neutrino flux and found it's very important for upgoing $\widetilde{\tau}$ and muon production. The event rates are also given, the quintessino-LSP scenario predicts more NLSPs than that of gravitino-LSP. The numeric results show that km-scale detectors are hopeful to get some positive results.

The possible signals may provide a direct evidence for supersymmetry theory, furthermore, it can also offer a potential solution for dark matter problem.

Acknowledgments

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